*Extension Note*

**BC Journal of Ecosystems and Management**

# Equilibrium forest age structure: Simulated effects of random wild fires, fire control, and harvesting

**Hugh J. Barclay[1], Tina Schivatcheva[2], and Chao Li[3]**

## Abstract

Historically, fire has been one of the main determinants of age structure in the forests of British Columbia, but in the face of recurring fires and other disruptive processes, achieving a stable forest age-class structure for sustainable harvesting is a challenge. The present paper investigates possible interactions of fire with harvesting and fire control, and their effects on age structure of a pine forest with varying fire-cycle lengths and fire-size regimes. We used simulation to determine the effects of the frequency and size of fires, fire control, and harvesting on the equilibrium age distribution of a forest. For small fires, resulting equilibrium age-class distributions were all declining, whereas for large fires, equilibrium was never achieved. Volume available for harvest was much greater when fires were infrequent. Harvest increased with fire control, but decreased with harvest age. In this simulation, the combination of intensive fire control and early harvesting optimized wood volume production. Awareness of the implications of particular fire regimes on sustained forest yield can inform design of better forest management and fire protection strategies.

**KEYWORDS:** *age structure, British Columbia, equilibrium, fire control, forest fires, harvesting, sustained yield.*

## Contact Information

1 Research Scientist, Natural Resources Canada, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5. Email: Hugh.Barclay@NRCan-RNCan.gc.ca

2 Faculty of Politics, Psychology, Sociology and International Studies, Selwyn College, Grange Road, Cambridge, UK CB3 9DQ. Email: joytinas@hotmail.com

3 Research Scientist, Natural Resources Canada, Northern Forestry Centre, 5320–122 Street, Edmonton, AB T6H 3S5. Email: Chao.Li@NRCan-RNCan.gc.ca



Barclay, H.J., T. Schivatcheva, and C. Li. 2009. Equilibrium forest age structure: Simulated effects of random wild fires, fire control, and harvesting. *BC Journal of Ecosystems and Management* 10(2):108–114. *www.forrex.org/publications/jem/ISS51/vol10_no2_art9.pdf*

## Introduction and background

In British Columbia, fires burn on average over 60 000 ha of forest lands annually, and fire is one of the most pervasive natural disturbance agents of forest ecosystems. One long-term goal of sustainable forest management is a relatively stable source of wood (at the scale of an area that might supply a large mill), and a stable forest age-class structure has become the goal of many forest management practices. In the absence of disturbances, this forest management goal could easily be achieved, particularly as stand-level variations can be compatible with overall landscape-level stability in age-class structure. However, in the face of recurring fires and other disruptive processes (such as mountain pine beetle, see Figure 1), forest planning becomes more difficult, requiring knowledge of the effects on the forest of a wide variety of environmental factors (e.g., habitat heterogeneity, weather patterns, fire size and frequency, insect outbreaks, species mix, and age distributions). Logistical factors such as access roads and mill capacity are also a consideration. In order to understand the impacts of these different factors, it is important to gain knowledge of the interactions among them, as well as of their main effects.

Ecological modelling is a tool that can be used to gain such understanding, and the present paper describes ecological modelling of interactions of fire with harvesting and fire control, and their effects on age structure of a lodgepole pine forest with varying fire-cycle lengths and fire-size regimes. Such effects on age structure have been noted by Keane et al. (2002) and Taylor and Carroll (2004). Also, Arno (1980) found that fire in lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) forests has been more frequent than previously thought.

Even before these effects were observed, Van Wagner (1978) showed by means of modelling that if small (1-ha) fires are randomly ignited in a million-ha mosaic, the resulting age distribution on an areal basis will stabilize and closely follow an age-class structure characterized by more younger trees and fewer trees in mature and older age classes (i.e., an exponential distribution). Later Boychuk and Perera (1997), Armstrong (1999), and Li and Barclay (2001) showed that if fires are large and infrequent, the age distribution will never stabilize and irregular oscillations will continue indefinitely.

*One long-term goal of sustainable forest management is a relatively stable source of wood, and a stable forest age-class structure has become the goal of many forest management practices.*

We have used modelling to examine how the current age-class structure of British Columbia's forests may have come into being and how this age structure depends on various factors. We chose to look primarily at fire control and harvesting—ignoring all the other features of the system that obviously have an effect, such as weather and major catastrophes—for two reasons: first, both fire control and harvesting are under the control of the forest manager, and second, the results are clearer if only a few factors are examined.

Long-term planning requires some degree of stability, and results from equilibrium models are clearer than from transient runs in revealing the effects of parameter manipulations. This was the rationale for the lengthy simulation time used in this study (2000 years for each run of the model; see Barclay et al. 2006 for details), but we acknowledge that real forests are rarely, if ever, at equilibrium.

There are many styles of modelling, but we chose Monte Carlo simulation as it lends itself to spatial


BC Ministry of Forests and Range

**FIGURE 1.** The Tweedsmuir fire (2003) in a lodgepole pine forest affected by the mountain pine beetle.

modelling. In Monte Carlo simulation, random numbers are used to determine the action of model factors. The main factors explored by the current study are fire control and harvesting as well as ignition probability (related to fire return rate) and fire size.

### Initial condition of the forest

Our model uses a square 1 000 000-ha tract (mosaic) of pure lodgepole pine forest. The initial age structure of the forest in each simulation was established as an exponential distribution (following van Wagner 1978) with a mean age of 100 years.

### Fire characteristics

We modelled the impact of stand-replacing crown fires rather than low-intensity surface fires—while they are a component of the fire regime in lodgepole pine, low-intensity fires are not usually stand replacing and have little effect on the resulting mosaic of age structures (Stuart 1983; Agee 1990).

**Fire size –** Seven maximum fire sizes were used: 1 ha, 10 ha, 100 ha, 1000 ha, 10 000 ha, 100 000 ha, and 1 000 000 ha. These fire sizes encompassed the observed range in British Columbia—between 1990 and 2000, fires in stands with greater than 60% lodgepole pine ranged from 0.1 ha to 953 ha, with a mean of 19 ha (BC Ministry of Forests and Range, Forest Practices Branch, Seamless Forest Cover Inventory [2000] of British Columbia, unpublished data). In severe fire years, larger fires often occur. Random numbers were also used to determine whether a fire occurred at a given location as well as the ultimate size of the fire once it was initiated. Fire size was determined by a random draw from a truncated exponential distribution, and scaled to yield a mean fire size of 0.125 times the maximum size; for example, if 100 000 ha was the specified maximum fire size, then fire sizes could be any whole-numbered value between 1 and 100 000 ha, and the mean of many such determinations would be 12 500 ha.

**Ignition probability –** Three ignition probabilities were used: 0.05, 0.01, and 0.004. Each cell in the mosaic had the same probability of being ignited and burning in any given year.

**Fire progression –** Fires were constructed by first determining whether a given cell would burn, and if so, then determining fire size. Once that was done, adjacent cells were ignited in concentric squares until the required fire size had been achieved. Thus, the burn probability combined with the mean fire size determined the fire return rate. We assumed that once a cell (i.e., 1 ha) ignited, it burned completely and there was no salvageable timber left.

### Fire suppression

In simulating fire control (modelled at 0, 50, 80, and 95% of fires suppressed), the whole fire was disallowed from burning, including the hectare in which the fire started.

### Harvest age

Simulations were run for harvest ages of 80, 100, and 120 years. To model the effects of fire size on harvest volume, we kept the fire return interval constant by adjusting burn probability and maximum fire size simultaneously. Thus, as maximum (and mean) fire size increased, burn probability decreased while the product of the mean fire size and burn probability remained the same, thus putting the focus on fire size itself.

## Results and discussion

To summarize results described in the full-length report on this study (Barclay et al. 2006), modelling showed that ignition probability significantly affected the mean forest age, and mean age declined as ignition probability increased. A stability index was used to assess the extent to which equilibrium had been achieved in the various simulations. For fires of relatively small size (< 10 000 ha), an equilibrium age-class structure was achieved after a few hundred iterations (simulated years) of the model. In these cases, the equilibrium age distributions were close to the exponential distribution, as predicted by Van Wagner (1978). Because these results indicate that predictable age-class structure is achievable under such a disturbance regime, this simplifies planning of replanting and harvesting schedules. For fires of the largest sizes (i.e., > 100 000 ha), equilibrium was never established and age classes tended to vary considerably over time. Results determined at the stand level in this study were accumulated to yield landscape-level results so that comparison with models at both scales would be possible.

In terms of fire control and harvest, amounts harvested decreased with increasing age at harvest (80, 100, or 120 years; Figure 2a), and these differences were most evident for high ignition probability. It is a

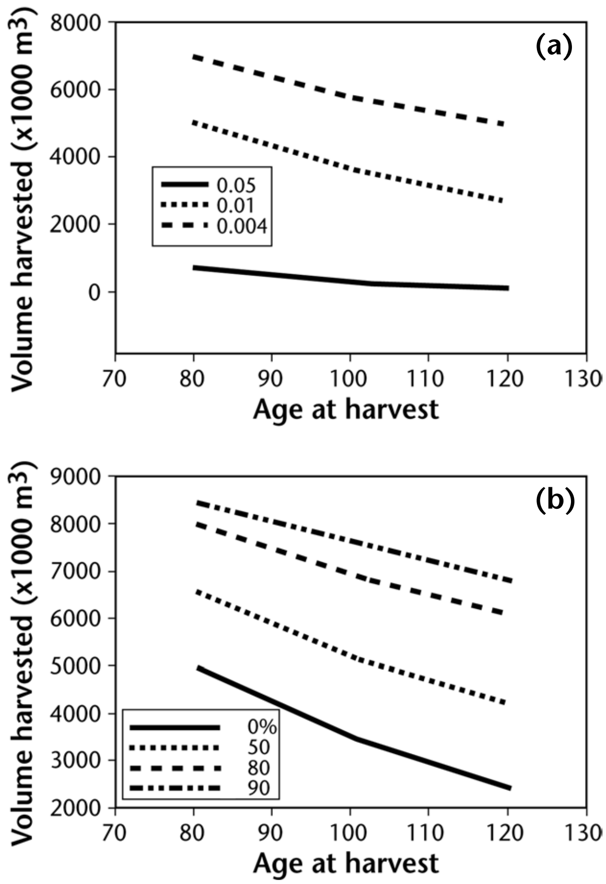


**FIGURE 2.** Volumes harvested with three harvesting ages (80, 100, and 120 years), three ignition probabilities, and four levels of fire control: (a) volume harvested (thousands of cubic metres) vs. age at harvest for three ignition probabilities (0.05, 0.01, and 0.004);
(b) volume harvested vs. age at harvest for four levels of fire control (0, 50, 80, and 95% of fires suppressed).

truism of forest mensuration that the greatest volume harvestable would be at the culmination of the mean annual increment (MAI); from Smithers' (1961) yield tables for lodgepole pine, it was calculated that the culmination of MAI in British Columbia occurs just after age 70 for all site indices tabulated, so the results derived here with fires agree with conventional wisdom as well as with the results of Reed and Errico (1986). The largest harvest was for low ignition probability, early harvest, and 95% fire control, although fire control alone had a pronounced effect on harvest for larger ignition probabilities (Figure 2b). Mean forest age also increased with fire control (0, 50, 80, and 95% of fires suppressed) and so did the volume harvested (Figure 2b). Although it may be argued that high rates of fire control have contributed to the present problems with intense fires and beetle infestations, harvesting of lodgepole pine was not appreciable until the 1960s or 1970s, and this also played a large part in predisposing the forest to fire and beetle problems (Taylor and Carroll 2004).

## Comparison with observed fires and other studies

Simulated forests with no fire control or harvesting approximated the forest age-class distribution resulting from the natural fire disturbance regime. As fire control and harvesting were introduced, the forest age-class structure shifted to the right and became less regular (Figure 3a). Initially, a run of the model was made in which fire control and harvesting occurred only during the last 100 years of the simulation. Then, a simulation with fire control alone yielded a peak in the 80–100-year class. The results for fire control and harvesting were similar to fire control alone. To compare these results with a real forest, data were obtained for lodgepole pine forest in British Columbia's Lakes Timber Supply Area, a tract of almost 1 million ha and subject to both fire control and harvesting. For the past few decades, this area has also been ravaged by mountain pine beetle infestations, and the age distribution has been reduced to an earlier seral stage (Figure 3b).

The distributions based on real data are much further from equilibrium than those from the simulated data. However, since fire is the only source of disturbance in the model, its effects are less extreme than those in nature, where several sources of disturbance often act simultaneously.

Our fires span the range observed in western Canada from 49 ha to 9132 ha in Kananaskis Provincial Park (Hawkes 1979) and from 45 ha to 708 172 ha in northern Alberta (Armstrong 1999). In British Columbia, fire size is often limited by the size of valleys, and may be bounded by creeks and other natural barriers (Andison 1996). These trends would make long-term age distributions in southwestern Canada more stable than those in boreal regions for similar-sized inventory regions. Instability in age distribution probably results in part from fire control and harvesting, both of which have only been initiated in the past century, as well as from insect attack.

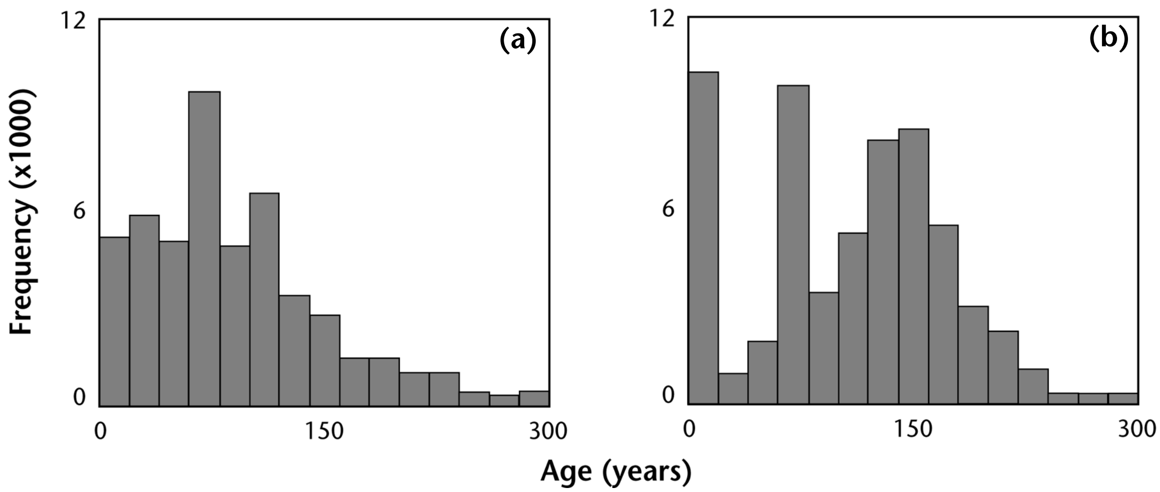


**FIGURE 3.** Forest age-class structures: (a) forest age-class distribution from the modelled simulations in which 50% of fires were controlled from 1900 to 1950, and then 95% of fires were controlled from 1950 to 2000; also, 300 ha per year were harvested from 1900 to 1960, and then 1500 ha per year were harvested from 1960 until 2000; (b) forest age-class distribution from the Lakes Timber Supply Area (54°N, 125°W). The frequencies of both are in thousands of stems.

## Management implications

Sustainable forest management requires finding the balance between social, economic, and environmental considerations, and this discussion acknowledges that maximizing volume harvested is only one of many objectives to consider. In principle, to manage the public forest lands on a sustained-yield basis, the amount of timber harvested annually ($m^3$) should not exceed the rate of annual growth less losses due to natural causes or human activities, otherwise the mean age of the forest will decline (Reed and Errico 1986). To use a simple equation, if the harvestable biomass of a forest area is $B$, the annual growth is $G$, the harvest is $H$, and the total losses to fire, insects, disease, and other natural mortality is $M$, then the progression of harvestable biomass from one year to the next is: $B_{i+1} = B_i + G - H - M$. So, if $H > G - M$, then $B_{i+1} < B_i$, where $i$ and $i$+1 represent successive years. Yet, fires are an integral part of forest ecosystem dynamics and play a significant role in the development of the forest. Thus, an inherent challenge of sustainable forest management is to balance various planning objectives, such as accommodating natural fire disturbance regimes and achieving sustained yield. Awareness of the implications of particular fire regimes on sustained forest yield can enable design of better forest management and fire protection strategies.

From the perspective of volume production or short-term planning for timber, the best combination of fire control and harvesting is intensive fire control and early harvesting. Indeed, if harvesting is strictly for fibre production, it could be even earlier than the 80 years used in the model, as the culmination of MAI is just above age 70 for lodgepole pine. In addition, there would be a greater return on fire control investments with early harvesting. Fire size has little effect on the volume harvested provided the fire return interval is kept constant. Thus, a regime of few large fires has a similar effect on harvest potential as many smaller fires with the same fire return rate.

Long-term planning requires some degree of stability to ensure sustainable log flow and this can be achieved by keeping the size of the fires small. Yet, there is a tradeoff between stability of the age-class structure and volume produced, so an adaptive

*Awareness of the implications of particular fire regimes on sustained forest yield can enable design of better forest management and fire protection strategies.*

management paradigm might be appropriate in cases where an equilibrium forest age-class structure could not be achieved. Although the goal of a forest landscape characterized by equilibrium age-class structure may or may not be achievable in practice, it is a useful indicator of the productive potential of the forested landscape.

Although focusing on one aspect of the fire disturbance regimes and forest management interactions helps to improve our understanding of the forest age-class distribution, the impacts of fire on forest ecosystems are much more complex—fire, fire management, and forest management are linked through a complicated set of interactions. Therefore, to manage forest landscapes sustainably, fire management, timber supply policies, and overall forest management considerations should work together to ensure the sustainable management of public forest lands.

*There is a tradeoff between stability of the age-class structure and volume produced, so an adaptive management paradigm might be appropriate in cases where an equilibrium forest age-class structure could not be achieved.*

## Acknowledgements

We thank Dr. Les Safranyik and Dr. Brad Hawkes of the Canadian Forest Service for discussions and information, and Gurp Thandi for obtaining the fire sizes from the BC Ministry of Forest and Range fire data that they shared with the Canadian Forest Service. This study is part of an ongoing project funded by the Government of Canada through the Mountain Pine Beetle Program, a 6-year, $40-million initiative administered by Natural Resources Canada, Canadian Forest Service. Additional information on the Government of Canada-supported Mountain Pine Beetle Program may be found at:
*http://mpb.cfs.nrcan.gc.ca*

## References

Agee, J.K. 1990. The historic role of fire in Pacific Northwest forests. *In* Natural and prescribed fire in Pacific Northwest forests. J.D. Walstad, S.R. Radosevich, and D.V. Sandberg (editors). Oregon State University Press, Corvallis, OR. pp. 25–38.

Andison, D.W. 1996. Managing for landscape patterns in the sub-boreal forests of British Columbia. PhD dissertation. University of Toronto, Toronto, ON.

Armstrong, G.W. 1999. A stochastic characterization of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. Canadian Journal of Forest Research 29:424–433.

Arno, S.F. 1980. Forest fire history in the northern Rockies. Journal of Forestry 78:460–465.

Barclay, H.J., C. Li, B. Hawkes, and L. Benson. 2006. Effects of fires size and frequency and habitat heterogeneity on forest age distribution. Ecological Modelling 197:207–220.

Boychuk, D. and A.H. Perera 1997. Modeling temporal variability on boreal landscape age-classes under different fire disturbance regimes and spatial scales. Canadian Journal of Forest Research 27:1083–1094.

Hawkes, B.C. 1979. Fire history and fuel appraisal study of Kananaskis Provincial Park, Alberta. MSc thesis. University of Alberta, Edmonton, AB.

Keane, R.E., K.C. Ryan, T. Veblen, C.D. Allen, J. Logan, and B.C. Hawkes. 2002. Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. General Technical Report RMRS-GTR-91.

Li, C. and H.J. Barclay. 2001. Fire disturbance patterns and forest age structure. Natural Resource Modeling 14:495–521.

Reed, W.J. and D. Errico. 1986. Optimal harvest scheduling at the forest level in the presence of the risk of fire. Canadian Journal of Forest Research 16:266–278.

Smithers, L.A. 1961. Lodgepole pine in Alberta. Canada Department of Forestry, Ottawa, ON. Bulletin No. 127.

Stuart, J.D. 1983. Stand structure and development of a climax lodgepole pine forest in south-central Oregon. PhD thesis. University of Washington, Seattle, WA.

Taylor, S.W. and A.L. Carroll. 2004. Disturbance, forest age, and mountain pine beetle outbreak dynamics in BC: A historical perspective. *In* Mountain pine beetle symposium: Challenges and solutions. T.L. Shore, J.E. Brooks, and J. Stone (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Information Paper BC-X-399, pp. 41–51.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8:220–227.

**ARTICLE RECEIVED: February 5, 2007**
**ARTICLE ACCEPTED: April 27, 2009**

Production of this article was funded, in part, by the British Columbia Ministry of Forests and Range through the Forest Investment Account–Forest Science Program.

# *Test Your Knowledge . . .*

***Equilibrium forest age structure: Simulated effects of random wild fires, fire control, and harvesting***

**How well can you recall some of the main messages in the preceding Extension Note?**
**Test your knowledge by answering the following questions. Answers are at the bottom of the page.**

1. What shape will the age-class distribution eventually assume if the forest is subject to constant and age-independent mortality and if no other sources of disturbance exist?
2. In this study, why did the amount of harvest increase as harvest age decreased?
3. Our simulation found that a stable equilibrium was attained for the occurrence of many small fires, but not for a few large fires. Why is this?

## *ANSWERS*

*1. The exponential distribution—this distribution declines steadily from a high value at zero to a low value at the point of truncation on the right.*

*2. All three harvest ages considered were above the age of mean annual increment, at which age the maximum harvest would occur.*

*3. Many small fires tend to smooth out fluctuations when taken over a large area or landscape; very few large fires are too disruptive and produce large gaps in the age structure, and so the smoothing does not occur.*